Recruitment, Storage, Transport and Function of Wood in Northern California Streams

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Abstract

Forest management and policy can be improved by clarifying the complex influence of riparian processes on streams. To this end, we evaluated the recruitment, storage, transport, and the function of wood in 93 km of streams (drainage area < 70 km^2) in northern California across four coastal to inland regions with different histories of forest management (managed, less-managed, unmanaged). Reach scale variability in wood storage and recruitment is driven by variation in rates of bank erosion, forest mortality and mass wasting. These processes are controlled by watershed structure including locations of canyons, floodplains, and tributary confluences, types of geology and topography, and forest types and history of management. Forest biomass, mass wasting, and residence time of wood in streams influence regional scale variability in wood recruitment and storage. Average wood volumes in coastal streams are 5 to 20 times greater than inland sites due to higher forest biomass and mass wasting, and longer residence times of stream wood. Mortality recruitment was substantial across all sites (mean 50%) followed by bank erosion (43%) and more locally by mass wasting (7%). The distances to sources of wood from streams are controlled by recruitment process and tree height. Ninety percent of wood recruitment occurs within 10 to 35 m of the channel in managed and less-managed forests and up to 50 m in unmanaged Sequoia and coast redwood forests. Streamside landsliding extends the source distance. The recruitment of large wood pieces that create jams (mean diameter 0.7 m) is primarily by bank erosion in managed forests and by mortality in unmanaged forests. Formation of pools by wood is more frequent in streams with low stream power, indicating the relevance of environmental context. These findings can be used to improve riparian protection and inform spatially explicit riparian management.

Introduction

Protecting riparian sources of wood for streams is becoming a major component of forestry policy in western states (Bisson et al. 1987, Bilby and Bisson 2004). Examples include establishing riparian protection zones for wood recruitment (Young 2000), mandating in-stream wood abundance standards or targets (NMFS 1996), monitoring abundance of wood in streams (Schuett-Hames et al. 1999) and implementing in-stream wood restoration programs (Cedarholm et al. 1997). The processes of forest mortality, bank erosion, streamside landsliding, debris flows and wildfires govern the supply of wood to streams (e.g., Murphy and Koski 1989, Benda and Sias 2003). The spatial distribution of different wood recruitment processes within a watershed or across landscapes varies substantially because of the diversity in forest composition and age, topography, stream size, climate and the history of natural and human disturbances (e.g., floods, fires, logging).

Spatial and temporal variability in wood recruitment processes can complicate the management and regulation of in-stream wood in both headwater channels (non-fish bearing) and larger fish bearing streams. For example, the width of riparian buffers to protect wood recruitment to streams may vary depending on whether forest mortality, bank erosion, or mass wasting is the dominant recruitment agent. If wood recruitment from channel migration or streamside landsliding is important, protection measures may extend up hillslopes beyond the streamside riparian forest (Reeves et al. 2003). Riparian forests could be managed for specific ecological objectives such as thinning dense young stands to increase the number of large trees (Beechie et al. 2000) or altering conifer-hardwood composition, strategies that require information on tree species and forest growth and mortality (Liquori 2006). Thus, an understanding of riparian processes that govern wood recruitment to streams can enhance protection strategies for riparian forests across physically diverse watersheds (Martin and Benda 2001).

In California, the management of riparian areas has become a major emphasis in forest management (Ligon et al. 1999, Berbach 2001). California's forest practice rules require a standard streamside buffer of a specified width along all fish bearing streams (45.7 m, 150 ft) and a subset of non-fish bearing streams, although some timber harvest is allowed within them. These buffer widths are based primarily on the presence or absence of fish or aquatic species, hillslope gradient, and yarding system, with no consideration of watershed to regional scale variability in riparian processes. In 2010 California adopted new forest practice rules that allow for a more site specific, spatially explicit approach to riparian management (CAL FIRE 2010).

Previous studies in California do not adequately characterize watershed to regional variability of wood recruitment to streams. For example, Harmon et al. (1986) and Lisle (2002) compiled in-stream wood volumes across several regions in California, although most information was collected in humid north coastal areas that used disparate measures of in-stream wood. In coast areas, Keller et al. (1995) documented the abundance and effects of old growth redwood logs on channel morphology and Wooster and Hilton (2004) measured in-stream wood volumes and accumulation rates. Also in the north coast region, Benda et al. (2002) estimated the relative contribution of forest mortality, bank erosion, and landsliding recruitment to streams in managed timberlands and in old growth coast redwood forests. Studies in the Sierra Nevada have focused on wood function and transport, including following fires (Berg et al. 1998, 2002) and on in-stream wood abundance and function in managed timberlands and old growth forests (Ruediger and Ward 1996).

Despite these studies, little information exists on the spatial variability in wood recruitment and its effects on channel morphology across different forest types and in the more inland regions of California. Accordingly our study objective was to identify the processes that control variability in recruitment and storage of in-stream wood across four geomorphic provinces in northern California. We applied a wood budget approach (e.g., Benda and Sias 2003) to quantify the processes and rates of wood recruitment along approximately 74 km of stream in forested mountain basins of 1 to 30 km^2, including both managed timberlands and unmanaged (old growth) parklands. We also evaluated some aspects of wood transport in streams and the role of wood in aquatic habitat. Our comparative analysis is used to better understand the range of variability in wood supply and storage and to evaluate how differences in landscape and watershed attributes (climate, topography, geology), forest management (managed, less-managed, unmanaged) lead to differences in wood abundance. Some implications of this study for riparian forest management are discussed.

Study Areas

Sixty-five kilometers of channels were surveyed in four California geomorphic provinces (California Geological Survey 2002) including the Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada (west slope) (Table 1, Figure 1). Study reaches were selected in basins of less than 30 km^2 (Figure 2) to minimize the effects of fluvial redistribution of wood (e.g., Seo and Nakamura 2009) and thereby to ensure that adequate amounts of wood were available for identifying the processes of recruitment (mortality, bank erosion, mass wasting). To expand the scope of the regional analysis, we included field data from a previous study we conducted using the same methods in the northern Coast Range, encompassing nine kilometers of streams in basins less than 30 km^2 (Benda et al. 2002). The two studies combined cover a surveyed length of 74 kilometers. To evaluate wood transport, an additional 19 km of stream reaches in basins draining areas from 30 to 70 km^2 were included to capture potentially longer transport distances in larger streams. In total, data on wood recruitment, storage and transport from 93 kilometers of streams are evaluated in this paper.

The study focused on fish bearing streams but also included smaller headwater (non-fish bearing) channels. The study sites encompassed a range of channel gradients, widths, drainage areas, and forest biomass (Figure 2). To compare regional differences in wood volumes, recruitment processes, and distances to sources of wood, the surveyed reaches were stratified into nine groups based on four geomorphic provinces and three forest management groups (managed, less managed, unmanaged) (Table 1, Appendix).

Managed forests include private timberlands with individual trees less than 100 years old, less-managed forests include public and private timberlands with longer harvest rotation and containing individual trees up to 200 or more years old, and unmanaged forests include old growth public parklands. A description of the forest metrics and harvest history for private managed and less managed forests is included in the Appendix. The majority of channels surveyed were in managed forests (51 km), followed by less-managed (15 km), and unmanaged forests (11 km) (Table 1).

Coast Ranges. Surveys took place in the Ten Mile and Noyo River watersheds near Fort Bragg, California (Figure 1). Sites from the Benda et al. (2002) study included tributaries of Redwood Creek (Redwood National and State Parks) and tributaries of the

Van Duzen River. The Mediterranean climate of the northern Coast Ranges is characterized by high annual precipitation (150-200 cm) that supports the coastal dominant species of coast redwood (*Sequoia sempervirens*), followed by Douglas-fir (*Pseudotsuga menziesii*) inland. Tan oak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and Live oak (*Ouercus wislizenii*) are mixed with conifers inland, while red alder (*Alnus rubra*), willow (*Salix lasiandra*), and big leaf maple (*Acer macrophyllum*) are the dominant deciduous tree species in riparian areas. Geology is mostly Franciscan mélange (Complex), a mixture of highly deformed and weakly metamorphosed sedimentary rocks, with some interbedded marine volcaniclastic sediments (Cashman et al. 1995). The mechanically weak rock in combination with heavy rainfall and tectonic uplift has created a steep landscape highly prone to mass wasting that produces some of the highest erosion rates in the continental United States (Nolan and Janda 1995).

Klamath Mountains. Study sites in the Klamath Province included tributaries of the Trinity River (Figure 1). The climate of the Klamaths has an annual average precipitation of approximately 130 cm/yr falling as a mixture of rain and snow at the higher elevations. The riparian forest community is comprised of mixed conifers dominated by Douglas-fir, and also includes ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*). Riparian deciduous species include white alder (*Alnus rhombifolia*), Pacific dogwood (*Cornus nutallii*), big leaf maple, and black oak (*Quercus kelloggii*). The geology consists primarily of metavolcanic, metasedimentary, and granitic rocks, with some glacial deposits at higher elevations (Harden 1997).

Cascade Range. Study locations focused on tributaries to Antelope and Battle Creeks of the Sacramento River (Figure 1). The Mediterranean climate of the Cascades is characterized by moderate annual precipitation that averages 110 to 120 cm/yr. The riparian forest community is comprised of mixed conifers dominated by ponderosa pine, and includes sugar pine, Douglas-fir, incense cedar, and white fir. Riparian deciduous species include white alder, Pacific dogwood, big leaf maple, and black oak. Cascade Range geology in the vicinity of the study areas include gently sloping volcanic tablelands interspersed with volcanoes and their remnants, including Lassen Peak and Brokeoff Mountain (Harden 1997).

Sierra Nevada. Study locations in the Sierra Nevada Province included tributaries to the Yuba, American, and Stanislaus Rivers (Figure 1). The Sierra's climate is characterized by cold winters and moderate annual precipitation that occurs as both rain and snow primarily between late fall and early spring and averages from 103 to 128 cm/yr. Unlike the other geomorphic provinces in this study, Sierran annual peak flows generally occur during the spring snowmelt, while mid-winter rainfall on snow cover has produced all the largest floods in major Sierra Nevada rivers (Kattelmann 1996). The riparian forest community in the study areas is comprised of mixed conifers, including ponderosa pine, sugar pine, Douglas-fir, incense cedar, white fir, Lodgepole pine (*Pinus contorta*), and jeffrey pine (*Pinus jeffryi*). Noble fir (*Abies procera*) and red fir (*Abies magnifica*) are also present at higher elevations of some areas, while giant sequoia (*Sequoiadendron giganteum*) is dominant in the old growth (unmanaged) site. Riparian deciduous species include varying proportions of willows, alders, maples, Pacific dogwood, and occasional black cottonwood (*Populus trichocarpa*). The Sierra Nevada is a tilted fault block composed of granitic, metamorphic, and volcanic rocks.

Methods

Wood Recruitment

We evaluated wood recruitment using a wood budget where the mass balance of wood is governed by input, output, and decay, a relationship expressed as:

$$\Delta S = [I\,\Delta x - L\,\Delta x + (Q_i - Q_o) - D]\,\Delta t \qquad (1)$$

where ΔS is a change in storage within a reach of length Δx over time interval Δt. Change in wood storage is a consequence of wood recruitment (I); loss of wood due to overbank deposition in flood events and abandonment of jams (L); fluvial transport of wood into (Q_i) and out of (Q_o) the segment; and in situ decay (D) (Benda and Sias 2003).

Total wood input (I) can be summarized as:

$$I = I_m + I_f + I_b + I_l + I_e \qquad (2)$$

including tree mortality by suppression, disease, or sporadic blowdown (I_m); concentrated toppling of trees following stand-replacing fires and windstorms (I_f); punctuated inputs from bank erosion (I_b); wood delivered by landslides, debris flows, and snow avalanches (I_l); and exhumation of wood buried in the bed or bank or the recapture of wood previously deposited on the banks (I_e).

We focused on wood recruitment (I). Thus, we ignored over bank deposition of wood (L) and did not analyze wood flux due to fluvial transport (Q). We did assess certain aspects of fluvial transport of wood (such as spacing between log jams) and used that data and a transport model (Benda and Sias 2003) to predict mean transport distance over the lifetime of the pieces. Although we observed (but did not measure) exhumation of buried wood in debris flow and alluvial deposits in coastal streams, we set I_e to zero because we could not date the partially buried wood (necessary for estimating recruitment rates). Because decay of wood mass occurs primarily through loss of density rather than volume (Hartley 1958), we omit loss of volume from decay in Eq. 1 since such loss would be insignificant during our budget periods of up to four decades. Our study sites did not include areas of recent fires and thus post fire toppling of trees (e.g., Harmon et al. 1986). We also did not encounter concentrated toppling due to intense windstorms (e.g., Reid and Hilton 1998). Given these constraints Equation 1 reduces to:

$$\Delta S/\Delta t\, \Delta x = (I_m + I_b + I_l) \qquad (3)$$

Although wood recruitment can be calculated using channel length or area, we use area to eliminate dependency of recruitment on channel width (e.g., an increasing volume of trees enters channels of increasing width) to support comparative analysis across channels of different sizes and across the four physiographic regions. We also report wood storage per unit channel length.

Fluvial Transport of Wood

Fluvial transport and redistribution of wood in streams are important when considering the role of headwater streams (non-fish bearing) on the wood supply to larger, fish bearing channels. We applied a wood transport model (Benda and Sias 2003) in order to examine how a few landscape factors (channel size, tree size, jam spacing and longevity) impose constraints on wood transport.

In that model, the transport distance (ξ) over the lifetime of wood is predicted by:

$$\xi(x,t) = L_j * (T_p/T_j) * \beta^{-1}(x,t) \;\; for \; T_p >= T_j \, , \qquad (4)$$

where ξ is the mean transport distance [m] over the lifetime of a piece of wood; L_j is the average distance between transport-impeding jams; T_p is the lifetime in years of wood in fluvial environments; T_j is jam longevity in years; and β is the proportion of channel spanned by a jam (Benda and Sias 2003). In this derivation, transport is limited to inter-jam spacing and it can become a multiple of jam spacing (L_j) when the lifetime of mobile wood exceeds jam longevity (T_j). In the absence of measurements on how wood transport is affected by the proportion of a channel spanned by a jam, transport of wood is assumed to be inversely and linearly proportional to the ratio of piece length (L_p, pieces creating jams) to channel width (w) ($\beta = L_p/w$) (see Benda and Sias 2003 for additional details).

Field Data Collection and Analysis

We surveyed all pieces of wood within the bankfull channel that were greater than 10 cm in diameter (as measured in the middle of the log) and 1.5 meters in length (after Sedell and Triska 1977). Wood storage is reported in volume rather than number of pieces. Wood volume was calculated as a cylinder, using the piece length within the bankfull channel and the diameter at the midpoint of the piece. Volumes of root wads were not included and consequently wood volumes of such pieces are underestimated. For each recruited wood piece, the perpendicular slope distance from the bankfull channel edge to its source (e.g., bank erosion scarp, base of tree for mortality, top of landslide scarp) was measured using a laser rangefinder. To estimate recruitment rates of wood, the process by which each piece of wood entered the channel was identified (recruitment wood) for a subpopulation of all pieces (those where the source could be identified). Wood pieces were assigned one of four source categories: bank erosion (rootwad attached and bank erosion scarp evident), mass wasting (streamside landslide, earth flow, debris flow), mortality (senescence, disease, or blow down), or logging (saw marks). Pieces of wood that formed wood jams (accumulation of at least two pieces that blocked at least a third of the channel) were noted as 'key' pieces (e.g., Bisson et al. 1987).

The age of recruited wood (time since it was recruited to the stream) was dated using saplings (growing on logs) by counting their growth rings using an increment borer, or the bole or primary stem was cut with a saw and rings were counted. A count of branch nodes was also used to age woody vegetation growing near or on trees and overturned stumps. Recruited wood was assigned a decay class using a modified version of a snag classification system developed by Hennon et al. (2002). Categories included: (1) leaves or needles, (2) twigs (no needles), (3) full branches, (4) primary branches, (5) partial primary branches (nub), (6) no branches and hard wood, and (7) no branches and rotten wood.

To estimate ΔT in equation 3, the arithmetic mean age of recruited wood in the study reach was used. The proportion of wood in each decay class was based on number of trees, rather than on volume, to reduce the variability in ΔT that can arise due to variations in the temporal sequence of smaller or larger tree recruitment. Preferentially weighting the oldest wood in the calculation of ΔT (e.g., Murphy and Koski 1989) may yield an overestimate in the mean age of recruited wood. By using an arithmetic mean, this error is countervailed by the loss of wood with increasing age, a process that would tend to underestimate the mean age. While this error is not quantified, it is likely similar or smaller than errors typically encountered in mass transfer budgets in watersheds, such as in sediment budgets (e.g., Dietrich and Dunne 1978).

In this study, residence time refers to the length of time wood remains within a given reach. We estimated the residence time (turnover time) of wood in streams by dividing the total volume of wood (excluding logging-related wood) by the recruitment rate (e.g., Lienkaemper and Swanson 1987). This calculation assumes equivalence between the input and output of fluvially transported wood. Because estimates of wood recruitment are minimums considering that some transport of wood occurs (and input may not always equal output over short time periods), residence times likely represent minimum values (e.g., Wooster and Hilton 2004).

The relative proportion of wood by volume that entered streams is estimated from varying distances away from channels banks. The resulting cumulative distributions are referred to as 'source distance curves' (McDade et al. 1990, Robison and Beschta 1990).

Distances to each source of wood were used to construct curves for each study segment and aggregated for each region-forest management group.

Channel morphology was characterized every 100 to 200 m within the study segment reaches, including gradient using a laser rangefinder or clinometer. Bankfull width was estimated using a tape or laser range finder. The effect of in-stream wood on pool formation (with a residual depth over 0.5 m) was inventoried as well as other pool forming elements including bedrock, boulder, or hydraulic forcing (associated with meanders or side channels and tributary confluences).

Results

Watershed and Regional Scale Variability in Wood Storage and Recruitment

A principle study objective was to evaluate variation in wood storage and recruitment due to regional differences in forest management histories across northern California (Figures 1 and 2). Overall, conifers dominated recruited wood storage (mean 88%) with the exception of the Cascades less-managed forest site, where deciduous trees accounted for 83% of the in-stream wood volume (Table 1). Average diameters of recruited trees in the coastal sites ranged from 0.5 to 1.7 m. Average diameters of recruited trees were similar across the Klamaths, Cascades, and Sierras (range 0.33 - 0.9 m Table 1), with the exception of the Cascades less-managed forest group with an average diameter of 0.18 m, reflecting the dominance of deciduous trees at this site. Logging related wood averaged 7% across all sites with 22% occurring in coastal managed forests. Most of the logging-related wood in coastal channels appeared to be a legacy of tractor logging that occurred prior to 1970s forest practice regulations. Field crews also observed extensive incision of low order coastal streams, another result of legacy tractor logging where small streams were filled with slash and sediment for use as skid trails, landings, and roads (Burns 1972). Only a portion of all wood pieces across all regions could be directly linked to a recruitment process (range 20 – 60%, average 46%, Table 1) and thus wood recruitment rates and recruited wood storage volumes are based on a subsample of pieces. Volumes of total wood storage include all in-stream wood, including recruited, unknown, and logging-related wood (conifer and deciduous combined).

Processes and volumes of recruited wood were highly variable across all study sites due to variations in geology, topography, valley width, and channel morphology. For example, along a continuous 8,000 m segment of Pilot Creek (Sierra Nevada), high wood recruitment resulted from increased bank erosion along streams bounded by earthflows and from elevated tree mortality due to floodplain aggradation in braided channel sections (Figure 3A). In contrast, zones of low wood recruitment occur where bank erosion is lower in more stable valley and canyon sections with more competent banks (including bedrock banks). Spatially variable wood storage is also driven by punctuated wood recruitment from debris flows originating in steep headwater channels. Along a 1,000 m reach in the Klamath Mountains, wood from two debris flow deposits accounted for 27% of the recruited wood volume concentrated along 100-200 m channel reaches (Figure 3B).

Cumulative distributions are used to examine differences in total wood storage (m^3/ha, m^3/100 m) and wood recruitment rates (m^3/ha/yr) across the nine region-forest management age groups (each group had surveyed channel reaches that ranged from 900 m to 24 km in length, Table 1). There is significantly more wood storage per unit area in the coast-forest groups compared to inland groups ($p < 0.01$, Mann-Whitney test). Total wood storage averaged 850 to 1100 m^3/ha in both unmanaged and managed coastal forests compared to 200 m^3/ha or less in the Klamaths, Cascades and Sierras (Figure 4A). The coastal groups have, on average, 5 to 20 times higher wood storage compared to inland areas (Table 1). The high wood storage in unmanaged coastal forests is driven in part by the massive size and slow decay of coast redwood trees (biomass density up to 10,000 m^3/ha, Westman and Whittaker 1975) and a long stream residence time (168 yrs) (Table 1). Forest biomass is lower in coastal managed forests (490 m^3/ha) but the high wood storage there (compared to inland areas) may be related to longer residence times of stream wood (71 yrs, Table 1) and the substantial contributions of historical logging slash and mass wasting to the total wood volume (22% and 25% respectively, Table 1 and Figure 5).

There are differences in wood storage patterns between the remaining seven inland region-forest types. The Klamaths less-managed forest, Sierras unmanaged, and Sierras managed all have higher wood storage per unit area relative to the Cascades-unmanaged, Cascades-less-managed and Sierras-less-managed forests ($p < 0.05$, Mann-Whitney test) (Figure 4). This may be due to higher proportion of bank erosion related sources of wood storage in the higher volume sites (48% versus 33%, Figure 5A); bank erosion tends to supply trees with thick trunks that are of larger diameter than thinner tree tops recruited further away from the channel. Overall, the trend of wood storage generally decreases from the coast eastward to Klamaths, Cascades, and Sierra regions in concert with decreasing wood residence times and riparian forest biomass (Figure 6).

Although variations in wood storage provide information on regional and forest management (age) differences in riparian processes, rates of wood supply to streams (wood recruitment) may be more informative for riparian management (Benda and Sias 2003). Rates of wood recruitment (m^3/ha/yr) from chronic mortality, bank erosion, and landsliding were estimated based on the volumes of recruited wood and the mean age of recruited wood in each category. Where feasible, the age of recruitment for individual trees was determined based on field evidence (dependent saplings, adjacent vegetation). Where an age of recruitment could not be determined, an age–decay class relationship was used to assign ages for recruited trees. To calculate age-decay class relationships, we distinguished between humid coastal forests and the other three drier inland regions because of climate differences that may affect decay rates; we also differentiated between conifer and deciduous trees. For the coastal sites we combined age data from the northern redwood region contained in Benda et al. (2002) with data from the southern coastal sites that yielded 140 aged pieces for conifers and 40 pieces for deciduous trees. The mean ages were calculated for seven decay classes of conifer and deciduous trees individually and they ranged from 1 to 48 years (unpooled data, Table 2). As a result of variable decay rates, several age-decay classes overlapped which were pooled to create four decay classes that had different mean ages ($p < 0.25$, Tukey HSD) (pooled data Table 2). We calculated mean ages for recruited wood using the same technique for sites in the Klamaths, Southern Cascades, and Sierras (combined). We measured the ages of 225 conifers and 84 deciduous pieces; ages ranged from 1 to 40 years. The 7 decay classes were pooled into 4 classes (Table 3), similar to the coastal sites.

Because recruitment rates are calculated for each forest management group (involving multiple reaches), the sample size for recruitment rates is smaller than wood storage that is calculated at individual 100 m reach intervals. Consequently, we use region-forest management groups that had at least five sites for statistical comparisons, including coastal unmanaged and managed forests, Klamath less-managed forests, Cascades managed forests, and Sierras managed forests (Table 1). First, we consider wood recruitment by forest mortality. Because conifer trees dominate in riparian forests, forest mortality was typically higher for conifers compared to deciduous, with the exception of the Sierras (Table 4). Recruitment rates for mortality among the five region-forest management groups ranged between 1.9 and 6.3 m^3/ha/yr but were not statistically different ($p > 0.31$, Mann-Whitney test).

Wood recruitment by streamside landsliding occurred in the coastal, Klamath and Cascade regions, ranging from 11 to 22% of total recruitment (Figure 5B). Wood recruitment by landsliding contributes to the high overall wood recruitment rates in the coastal unmanaged and managed forests, as well as in the Klamath and Cascade less-managed forests (Figure 4). We also observed wood recruitment by landsliding in the Sierra streams, but in basins greater than 30 km^2 (which were not included to minimize the effects of fluvial redistribution in wood volume/recruitment).

Wood recruitment by bank erosion is important across all nine region-forest management groups, ranging from 22% to 63% of the total recruitment (Figure 5). Wood recruitment by bank erosion averaged 43% across all groups; no pattern due to forest age or physiographic region was observed. Wood recruitment rates by bank erosion among the five groups were not statistically different ($p > 0.32$, Mann-Whitney test) (Table 4).

Similar to the differences in wood storage between coastal forests and inland sites, wood recruitment rates between the two areas also varied (Figure 4). The coastal managed forests had the highest recruitment rates reflecting relatively large inputs from mass wasting (Figure 5B). Coastal unmanaged forests had the lowest recruitment rates reflecting low forest mortality rates (e.g., Benda et al. 2002), despite very high biomass densities (Table 1). The remaining inlands groups (Cascade managed, Klamath less-managed, and Sierra less-managed) show few differences in their rates, although Sierra managed had the highest rates (Figure 4).

We also examined whether channel size (width and drainage area) and channel gradient were related to spatial patterns of wood recruitment rates. Few relationships were detected, probably due to the spatially distributed nature of different wood recruitment processes (wind, bank erosion and streamside landsliding) with respect to channel size and slope (Figure 3). One exception occurs in managed coastal forests, where bank erosion recruitment was higher in small basins (<4.5 km^2) compared to larger watersheds (4.5 – 30 km^2) ($p < 0.13$, Mann-Whitney test). This may be due to historical tractor logging in which headwater coastal streams were often filled with slash and soil to create skid trails, roads, and landings (Burns 1972). As a result, many of these low order coastal streams are now highly incised (gullied) and disconnected from their floodplains with actively eroding banks (high bank erosion recruitment). Although absolute channel size is not a determinate in wood recruitment in our study (channels in watersheds < 30 km^2), other topographic and riverine controls are, including canyons, floodplains, mass wasting, tributary junctions and geology (e.g., Figures 3 and 7).

Variation in Source Distance of Wood Recruitment

Source distance curves quantify the proportion of riparian wood delivered according to distance away from the channel edge by bank erosion, forest mortality and landsliding (McDade et al. 1990; VanSickle and Gregory 1990). Shapes of source distance curves are strongly influenced by the processes of wood recruitment, particularly at the reach scale (Benda et al. 2002). For example, a majority of wood volume is recruited close to the channel edge where bank erosion dominates (Figure 7). Mortality recruitment extends the source distance curves away from the channel edge. Landslides extend the curves even further from the channel up the hillslopes. Where mortality dominates wood recruitment, forest management histories and thus tree age and height influence the source distance; managed forests with smaller trees have shorter source distances compared to less-managed and unmanaged forests with taller trees (Figure 7A). In managed forests of the Sierras and Cascades where no landslides were encountered, 90% of the wood originates from within 10 m of the channel; the remaining 10% is supplied from a distance equivalent to one tree height. Short source distances are related to bank erosion that dominates wood recruitment in managed forests of the Sierras and Cascades (62% and 63% respectively, Figure 5B). Shorter source distances are also found in deciduous forests. For example, 77% of wood recruited in the Cascades less-managed forests is from deciduous trees (Table 1), where recruitment from mortality is limited to small deciduous trees that skew the source distance curves closer to the channel (Figure 8B). In contrast, 90% of the wood originates from within 30 m of the channel in managed coastal forests (Figure 8A), where landslides comprise 22% of the recruitment rate (Figure 5B).

In less-managed forests with taller trees and contributions from landslides, 90% of the wood is derived from within 15 to 35 m of the channel (Figure 8B). In unmanaged and taller coast redwood and Sequoia forests, the source distance for 90% of wood recruitment is between 35 m and 50 m (Figure 8B).

Recruitment of Key Pieces and Formation of Pools

The diameter of key pieces of wood that form log jams ranged from about 0.3 m to greater than 1.5 m and averaged 0.72 m (Figure 9A). The majority of key pieces with diameters greater than 0.8 m are located in the coast unmanaged and coast managed regions, indicating the importance of large trees and the legacy of large older logs left in streams following mid-twentieth century logging (Table 1).

The majority of key pieces in managed forests is recruited by bank erosion (60 – 70%), while mortality supplies just over half of key pieces to streams in unmanaged forests (51- 52%); the remaining portion coming primarily from bank erosion (Figure 9B). Streamside landsliding is locally important in recruiting key pieces of wood in the coast, Cascades and Klamath Mountains (up to 25%). Data are not available on key pieces in unmanaged coastal forests. Pools in all study reaches (except in the Klamaths, no data) were associated with one of four pool-forming processes: hydraulic scour, bedrock, boulder, and wood. Wood formed pools averaged 35% and ranged from 9 to 78% across all region-forest management groups (Figure 10). Two of the three highest values (>50%) occurred in the coastal groups where channel gradients averaged 2 to 7% (Figure 2). Boulder-formed pools dominated in the Cascades and boulder and bedrock pools dominated in the Sierras. Hydraulic scour pools occurred mostly in low gradient (average 2.5%) channels that meander through meadows of the Sierras less-managed forests.

Wood in streams is often most effective at forming pools in lower gradient channels that have deformable sediment substrate, such as gravel or sand (Beechie and Sibley 1997). Combining the data from all regions, we found the highest proportion of wood-formed pools in association with the lowest stream power (Figure 10B).

Fluvial Wood Transport

Across the four study regions in northern California, field measurements of in-stream wood in basins less than 70 km^2 indicate the distance between wood jams (< 10 m in the smallest streams to several hundred meters in larger channels) increased with drainage area, the proportion of the channel spanned or blocked by jams (100% to 30%) decreased with drainage area, and jam age (45 years to less than 10 years) decreased with drainage area (Figure 11). All of these spatial trends are anticipated in fluvial wood transport (Benda and Sias 2003). The statistical regressions for these parameters, along with an assumed lifetime of wood in fluvial environments (T_p) of 100 years (using a 3%/yr wood decay rate, Benda and Sias 2003), are used in Equation 4 to predict wood transport. Predicted wood transport (over the lifetime of wood in streams) varied from less than 100 m to several thousand meters in channels with drainage areas of 1 to 75 km^2, with transport distance increasing with drainage area ($r^2 = 0.52$) (Figure 12A).

If fluvially mobile pieces are defined as log length less than channel width (e.g., Lienkaemper and Swanson 1987), then the percent of mobile pieces (out of the total inventoried pieces of wood) ranged from about 30% to almost 100%, providing a weak positive correlation ($r^2 = 0.54$) between mobile pieces and drainage area (Figure 12B).

Discussion

Comparison with Other Studies in California

How do our study results compare to existing information of wood storage and recruitment in California? The great natural variability in wood storage and recruitment observed at individual study sites and across the four regions (Figures 3 and 4) complicates comparisons of our measured values with other studies in California. Volumes of in-stream wood in unmanaged and managed coast redwood forests (using streams that were “cleaned” of wood in the post 1950-1960 logging period) were measured by Wooster and Hilton (2004). Our values in unmanaged forests are similar (Table 5), given the wide range of natural variability encountered in both studies. Our values in managed forests, however, are significantly higher compared to the Wooster and Hilton study (average 1000 versus 250 m^3/ha). Site history may explain some of the differences, where many of our study sites in managed forests included small streams with large quantities of logging debris primarily from tractor era logging (22% of total wood, Table 1) compared to the "cleaned" streams of Wooster and Hilton (2004). Similar quantities were reported by other studies in managed coastal streams, ranging from 279 m^3/ha (O'Connor 2000) to approximately 340 m^3/ha (O'Connor and Ziemer 1989, Lisle 2002).

Lisle (2002) also compiled wood volumes from unmanaged sites in the coast (redwoods), Klamaths, Cascades and Sierras and there are similarities and differences compared to our in-stream wood volume estimates (Table 5). Some of the differences likely arise from the disparate methods used to measure wood volumes between our study and the various estimates compiled by Lisle (2002). Although there is substantial variation across the studies (much of it likely due to the different field methods employed), the overall spatial pattern of decreasing wood volumes from coastal to inland areas is similar (highest in the coast, intermediate in the Klamath/Cascades, lowest in the Sierras).

A few past studies in California have included estimates for wood recruitment rates. Wooster and Hilton (2002) reported wood recruitment rates in unmanaged redwood and managed forests that ranged from 7 to 17.6 m^3/ha/yr (ave. 13.7 m^3/ha/yr) and from 2.3 to 15.2 (ave. 4.2), respectively. O'Connor (2000) reported a recruitment rate of 3.7 m^3/ha/yr for managed coastal forests. In the same forest types, our study results in unmanaged and managed forests ranged from 2.5 to 6 m^3/ha/yr (ave. 5 m^3/ha/yr) and from 3 to 11 m^3/ha/yr (ave. 10 m^3/ha/yr), respectively. The recruitment rates are similar in each forest type although the averages vary by a factor of 2 to 3, not unreasonable given the large inherent variability in wood storage and recruitment (based on ranges in both studies). The largest difference is Wooster and Hilton's (2002) estimate of wood recruitment in unmanaged redwood forests that was almost three times higher than managed forests. Our study indicated the opposite trend: recruitment rates in managed forests were two times higher than unmanaged forests. This may be due to the differences in the managed forests sampled between the studies, where Wooster and Hilton (2002) sampled managed streams that were historically cleaned of wood, some of our managed coastal streams were filled with logging related wood (slash) that may increase wood recruitment from bank erosion.

Evaluating tree mortality rates provides a way to reconcile the recruitment rate differences observed in managed versus unmanaged coastal forests. A wood budget allows estimates of forest mortality rates associated with mortality driven recruitment rates if riparian forest biomass (m^3/ha) is known (Benda and Sias 2003). Thus, using a wood budget, our previous study in northwest coastal California revealed that managed forests in the Van Duzen watershed have a higher forest mortality rate (1%/yr for conifer and 0.6%/yr for deciduous forest) compared to unmanaged (old growth) redwood forests (0.04%/yr for conifer and 0.02%/yr for deciduous) (Benda et al. 2002). We used data on replacement rate for unmanaged redwood forests from Viers (1975) in Benda et al. 2002 to develop an independent estimate of mortality rates in unmanaged (old growth) redwood forests of 0.02%/yr to 0.03%/yr. We also calculated conifer forest mortality rates in two of our other study areas along the coast (coast managed) of 0.26%/yr to 0.4%/yr for conifer and 0.09%/yr to 1.1%/yr for deciduous. These rates are similar to our previous estimate in managed forests in the Van Duzen watershed. Old growth redwood trees are known to have great longevity (500 to 1000 yrs are not uncommon, Noss 1999) due to a very low mortality rate. In alluvial flats, coast redwoods eventually die from wind-throw, failure to maintain balance, extremely large floods, and heart rot (Stone and Vasey 1968). We hypothesize that mortality rates in managed forests may be higher due to increased suppression mortality (tree competition) compared to older less-managed and unmanaged forests.

Forest Age Dependency on Mortality Rates and Wood Recruitment

How does forest mortality and thus mortality rates of wood recruitment vary from managed to unmanaged forests? Three of the study regions have wood recruitment data spanning managed to unmanaged forests. We omit the coast data because there is no ‘less-managed forest’ category and because unmanaged redwood forests have very low mortality rates (e.g., 0.025%/yr compared to 0.5%/yr for other coastal conifer forests, e.g., Franklin 1979). In the Cascades and Sierras, the managed forests had moderately high mortality recruitment rates that were higher than the less-managed forests (Cascades: 2.6 m^3/ha/yr versus 0.42 m^3/ha/yr; Sierras: 1.55 versus 0.9 m^3/ha/yr), but lower than the unmanaged forests (3.22 and 3.03 m^3/ha/yr) for Cascades and Sierras (Table 4). This pattern may reflect the forest mortality changes that accompany forest growth: managed forests have high mortality during the stem exclusion stage; less-managed forests have the lowest mortality due to vigorous growth; unmanaged (older) forests with increasing scenescence have the highest mortality rates (Spies and Franklin 1988). Because these rates are back-calculated (e.g., Benda and Sias 2003) and therefore preliminary, more direct measurements of mortality rates in forests would advance our understanding about how forest age influences wood recruitment rates.

The temporal pattern of mortality rates indicates that although mortality may be higher in managed forests, the wood recruited to the stream may be of smaller diameter and thus less beneficial from an aquatic habitat perspective (e.g., large wood creates large pools, Rosenfeld and Huato 2003).The exception may be small headwater streams (non-fish bearing) where smaller pieces of wood may function in sediment storage and the creation of small steps that reduce stream energy (Jackson and Sturm 2002). However, larger logs may be important in sediment storage in steep headwater streams that are prone to debris flows (May and Gresswell 2003). The lower mortality recruitment when trees are vigorously growing following stem exclusion may depress wood storage in streams. Wood storage may increase in the unmanaged (older) forests when forest mortality increases (Table 4).

Regional and Watershed Scale Variability in Wood Recruitment, Storage and Source Distance Curves

How does watershed to reach scale variability in recruitment and storage compare to regional scale variability? At the stream reach scale, spatial variability in wood recruitment, wood storage and source distances is the rule (Figures 3 and 7). Due to variations in bank erosion, mass wasting and mortality recruitment, wood storage can vary by a factor of 10 to 30. There are also significant differences in wood storage and wood recruitment rates across the four different regions. Wood storage (median) varies by three orders of magnitude with the coastal streams having the greatest volumes and the Cascades the least (Figure 4). Larger wood storage volumes in coastal streams are partly due to longer residence times (ave. 120 yrs, range 71 - 178 yrs) compared to the inland areas (ave. 18 yrs, range 2 - 48 yrs). Part of the reason for lower residence times at inland sites may be the steeper channel gradients in those landscapes (Figure 2) that can cause higher fluvial export of wood. Overall, total wood storage varies systematically along a 300 km west to east gradient (coastal to inland) in concert with decreasing wood residence times and riparian forest biomass (Figure 6). The scale of variation in wood storage within regions (individual watersheds) (as defined by the slope of the cumulative distribution in Figure 4) is generally less than the variation across the different regions. Other regional studies have also demonstrated significant variability in wood storage due to regional and more local geomorphic factors, such as in southeast Alaska (Martin 2001).

With regard to wood recruitment rates, individual region variability is similar to across region variability (Figure 4), with the exception of very high and low values associated with the coast managed and unmanaged forests respectively (Figure 4). The larger regional variations in storage appear to be associated with substantial differences in riparian forest biomass (particularly coastal sites, Table 1), mass wasting in the coastal areas, and the longer residence time of wood and legacies of historical logging in coastal sites.

Regional variability in source distance curves is driven by tree height, where the taller trees of the coastal redwood area have the greatest source distance (Figure 7), where a site potential tree (old growth) can be 80 m (270 ft) or taller (Viers 1975). Otherwise, reach scale variation in wood recruitment processes (bank erosion, landsliding and mortality) governs variation in source distances (Figure 7). The age of forests that influences tree height is an important source of variability; managed (younger) forests in all regions have the shortest source distances (Figure 8). Moreover, the occurrence of deciduous forests can dramatically shorten the source distances, driven by the concentration of deciduous trees located near channels.

Wood recruitment processes do not appear to vary by channel size in our study. Rather, spatial variation in wood recruitment processes are driven by changes in watershed attributes such as earthflows, debris flows, streamside landslides, valley width, channel morphology (e.g., braided channels), tributary junctions, and canyons (Figure 3). Many of these upland and riverine controls on wood recruitment are distributed in watersheds based on geology, topography, and river network characteristics of individual watersheds, and they are less influenced by absolute size of the channel.

Fluvial Wood Transport

The transport of wood by stream flow is an important consideration in the mass balance of in-stream wood. For example, it may be of interest to know the proportion of wood in fish bearing streams that originates from headwater channels (non fish-bearing). This may inform riparian protection strategies. In addition, wood transport may also affect the redistribution of pieces and the formation of wood accumulations (jams), including their size and spacing. This may have implications for the formation and spatial distribution of aquatic habitats throughout channel networks.

Relative to estimating wood recruitment rates in streams, estimating fluvial wood transport remains a more imprecise science. In this study we applied a simple model (Benda and Sias 2003), parameterized by field data (Eq. 4: jam spacing, jam related channel blockage, jam age, and wood decay), to make estimates of average wood transport in streams (over the lifetime of wood in streams). The results indicate that in small headwater streams, average transport distances may be a couple of hundred meters. Excluding potential transfer of wood by debris flows, this suggests that only the lower portion of headwater channels may transport woody debris to larger fish bearing streams. While the relationship between transport distance and channel size is moderate (r^2=0.52, Figure 12A), it could be used to create watershed scale maps of wood transport to help guide field studies or riparian protection strategies.

In contrast, Lassettre and Kondolf (2003) observed and modeled wood transport in a coastal stream, where 90% of the wood transport distances exceeded jam spacing during flood events ($\geq$ 15 yrs), suggesting low order channels may be a more important source of wood to larger fish-bearing streams. The differences in the two models suggest that further field measures and more sophisticated models are needed to clarify the magnitude of wood supplied from low to high order streams by fluvial transport. For example, Lassettre and Kondolf (2003) showed that jams are destroyed during certain magnitude floods or that flows overtop jams allowing wood transport past wood obstructions. Thus the parameter of jam longevity in Benda and Sias (2002) could be reduced based on flood magnitude or that effectiveness of wood capture by jams could be reduced during large floods. Further research on fluvial transport of wood at all scales is also merited because the majority of wood in streams is transported and cannot be identified by source (39 to 79% of the wood in our study, Table 1).

Effects of Wildfire on Wood Recruitment

This study focused on wood recruitment in live forests (managed to unmanaged) over a period of several decades and it did not include wood recruitment by post-fire toppling of dead trees. Following a stand replacing fire within a riparian forest, there often is a several decade period of heightened tree fall and thus wood recruitment to streams (Harmon et al. 1986). We are not aware of field-based estimates of post-fire wood recruitment in the context of a long term wood budget in California or elsewhere. The long-term effect of fire on wood recruitment should depend strongly on the frequency of fires in the riparian forest. Benda and Sias (2003) examined the role of stand replacing fires in the context of a wood budget using a simulation model. They estimated that fires in Pacific Northwest forests with an average recurrence interval of 500 yrs (west side of the Cascades) and 150 years (east side of the Cascades) contributed 12% and 55% respectively of the total wood supply to streams. This suggests that fire in drier regions of California (such as the Klamaths, Southern Cascades and Sierras) may be a substantial component of wood supply to streams. Following a heightened supply of wood through the loss of the forest, there should be a period (following decay and fluvial transport of wood downstream) where wood supply and storage in streams may be depressed, an outcome predicted by simulation models (Benda and Sias 2003) and observed in a Sierra stream following a wildfire by Berg et al. (2002). Further research is recommended on the supply of wood to streams following fires considering climate warming and anticipated increases in wildfire intensity and frequency in California.

Recruitment of Wood by Debris Flow

Small headwater streams typically comprise upwards of 60 - 70% of the stream network (Shreve 1969). Consequently, understanding the supply of wood from debris flows is critical when considering the contribution of wood from low order tributaries to larger fish-bearing channels in mountainous terrain (e.g., Burnett and Miller 2007). We observed wood recruitment from debris flows in both the Klamaths (Figure 3B) and Coast Ranges, but could not reliably determine the age of partially buried wood using decay classes. Thus, rates of debris flow inputs of wood in California remain unknown.

To make an estimate of debris flow recruitment of wood in California streams would require knowledge about the susceptibility of a headwater stream to debris flows and their recurrence intervals (e.g., Benda and Sias 2003, Miller and Burnett 2007). Neither of these factors is known well for California relative to other landscapes (e.g., Benda and Dunne 1997a, Miller and Burnett 2007), even though debris flows in headwater streams are documented in California (Kelsey 1980, Bertolo and Weiczorek 2005).

Implications for Riparian Management

From this study, we outline several implications for riparian management in California, with specific reference to wood supply and function in streams. Other factors such as thermal loading, erosion and sediment delivery, nutrient input, and terrestrial wildlife habitat requirements may dictate other riparian management considerations.

- There is significant variability in recruitment, storage and source distances of wood due to varying upland and riverine watershed attributes. The dimensions of riparian protection zones (width, location) could be spatially variable depending on the dominant wood recruitment process such as bank erosion, forest mortality and mass wasting associated with various geologic, topographic and river network controls.
- Ninety percent of wood recruitment comes from within approximately 30 m to 40 m of the stream in less-managed forests. Large old growth trees specific to Sequoia and coast redwoods have longer source distances upwards of 50 m or more. While source distances in old growth Douglas-fir forests have not been clearly established for California, findings by McDade et al. (1990) could be used

as a guide, where 90 percent of wood is recruited within 35 to 40 m of the stream channel in old growth Douglas fir forests of Western Oregon. These patterns could be used to design site-specific stream protection measures to ensure adequate wood recruitment to streams.

- Bank erosion is often a dominant process of wood recruitment to streams. Trees recruited by bank erosion include rootwads and thick trunks and therefore typically have larger diameters and more geomorphic influence on streams than smaller tree tops recruited further from the channel by mortality. For example, key pieces of wood that forms jams originate mostly from bank erosion. Consequently, streamside trees potentially recruited by bank erosion could be one focus of protection.
- Fluvial transport of wood may range from a couple of hundred meters in headwater streams (or less) to several thousands meters in larger streams. This information provides a first order approximation of the connectivity between fish and non-fish bearing streams with respect to wood flux, but requires additional research on fluvial transport of wood, and should also include the probability of wood transfer by debris flows.
- Because of large regional and watershed to reach-scale variability in wood recruitment and storage in streams, there is no apparent basis for "reference" wood storage targets or even distributions in restoration or monitoring. Spatial variability in wood loading over two to three orders of magnitude arises due to canyons, floodplains, earthflows, landslides, braided channels, and debris flows, combined with the temporal variability of wood recruitment due to a host of natural and human caused disturbances. Consequently, monitoring or restoration targets or distributions may be more appropriate for the source of wood (riparian forests), rather than where it ends up in streams.
- There are significant regional variations in wood storage and to a lesser extent wood recruitment. Recognition of watershed to reach scale variability in wood recruitment processes should incorporate regional scale variations.
- Episodic wood supply following wildfire in drier regions of California may be a substantial component of long-term wood recruitment to streams and thus salvage

logging in burned riparian areas could diminish this source (e.g., Reeves et al. 2006).

- Mass wasting sources of wood can be locally important in all regions but particularly in the coastal and Klamath landscapes. Use of predictive models could be used to delineate probable debris flow sources of wood.
- There are generally substantial differences between managed and older unmanaged forests in the volume of wood supplied to streams, the distance to sources of wood, and recruitment of key wood pieces that form pools. Tree heights of older (unmanaged or less managed) forests should be considered in the design of riparian buffers.

Findings from this study suggest that a spatially explicit approach to riparian management and regulation might be preferable to single width, uniform stream buffer requirements for different regions in California. A spatially explicit approach would involve custom, site specific design of buffer dimensions, locations and silvicultural options (CAL FIRE 2010), and may offer several advantages over uniform buffers. In certain locations, protection areas could be expanded, such as around biological hotspots (wide floodplains, tributary junctions, etc.) that are preferentially important for fish and wildlife. In other areas, buffers could be reduced, such as in areas where wood in streams plays a marginal role or where habitat is intrinsically poor. In headwater environments, protection could be tailored to address requirements for wood, thermal and sediment functions. The connectivity between headwaters and larger, fish bearing streams could drive protection in a subpopulation of headwater streams that are deemed important. This could include debris flow sources of wood and significant areas of nutrient flux.

There may be other benefits of a spatially explicit approach. Because riparian protection is based on an understanding of riparian-stream processes, enhancement or restoration could become an integral part of riparian management. This may include placement of wood in streams, creating gaps in tightly closed canopies for increasing sunlight (and increasing primary production), and the conversion of hardwood to conifers (in areas in need of large wood) or conversion of conifers to hardwoods (for enhanced food loading through deciduous litterfall). In addition, the increasing wildfire risk across the western United States threatens unmanaged riparian forests that may have higher fuel loadings compared to adjacent forests (Van de Water and North 2011). Protecting riparian forests from stand replacing fires may include fuel treatments (thinning small trees) and fire breaks. Finally, spatially explicit riparian management is best applied at the watershed scale so that protection strategies reflect the full suite of riparian and channel environments. A data rich watershed scale approach could offer other advantages, such as considering entire road networks as a riparian issue, including as sources of sediment, altered drainage and migration barriers. Implementing a spatially explicit approach to riparian management would require some field work in combination with GIS-based terrain mapping to predict wood recruitment, a task that has become more affordable with advancement in technology (e.g. Benda et al. 2007) compared with historical watershed analyses.

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Table 1. Information about each of the nine region-forest management groups including number of reaches, survey length, drainage areas, riparian forest biomass, wood volume and wood recruitment rate.

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Note:

Geomorphic Province and Forest Management	No. of Reaches (sites)	Total Survey Length (km)	Drainage Area (km^2)		Riparian Biomass Density (m^3/Ha)		% of Recruit Wood Volume		Mean Recruit Diameter (m)	% of Total Wood Volume			Total Wood Volume (m^3/Ha)		Total Recruitment Rate (m^3/Ha/yr)		Residence Time (yrs)
			Mean	σ	Mean	σ	Conifer	Deciduous		Unknown	Known Process (Recruit)	Logging (Cut)	mean	σ	mean	σ	
Coast Unmanaged	5	4.5	16.8	8.2	3941	1627	77	23	0.85	79	21	0	845	923	5.0	4.1	168
Coast Managed	34	20.7	6.4	6.9	490	409	74	26	0.43	57	20	22	1059	1545	11.4	15.1	71
Klamaths Less Managed	7	8.5	11.0	9.2	671	348	90	10	0.43	42	54	4	190	160	9.7	11.7	19
Cascades Unmanaged	3	4.2	19.6	9.4	902	363	94	6	0.41	39	60	1	13	10	6.5	3.5	2
Cascades Less Managed	2	0.9	23.5	3.2	196	42	17	83	0.18	45	55	0	54	45	8.7	9.3	6
Cascades Managed	6	5.5	6.0	5.9	596	129	90	10	0.33	32	53	15	107	136	8.6	14.6	13
Sierras Unmanaged	1	2.0	5.8	--[a]	--	--	89	21	0.40	40	59	1	166	114	7.6	--	--
Sierras Less Managed	2	5.2	16.3	5.6	258[b]	72	98	2	0.40	39	52	9	65	84	1.2	0.4	48
Sierras Managed	17	24.3	10.0	10.4	106[b]	95	91	9	0.34	49	37	14	226	289	9.2	19.4	20

a – only one reach sampled.

b – biomass density estimate not based on site specific data, as a proxy we use USFS (1996) estimates from the Sacramento Resourrce Area that includes the Sierras

Table 2. Age statistics for unpooled and pooled decay classes of recruited wood are shown for conifers and deciduous wood in the Coast Range of northwestern California.

Unpooled					Pooled			
Decay Class	**Mean**	**σ**	**n**		**Class**	**Mean**	**σ**	**n**
				Conifers				
Needle[a]	1.0	--	--		Needle[a]	1.0	--	--
Twig	4.1	1.5	12		Twig, Branch	5.0	2.4	25
Branches	5.9	2.7	13		Primary, Nub	17.9	15.1	30
Primary Branch	10.0	10.5	15		Hard, Rotten	42.4	27.6	85
Nub	25.7	15.0	15					
Hard	41.2	27.6	70					
Rotten	47.9	27.8	15					
				Deciduous				
Leave[a]	1.0	--	--		Leave[a]	1.0	--	--
Twig[b]	4.1	1.5	12		Twig[b], Branch	4.4	1.8	19
Branch	5.1	2.1	7		Primary, Nub, Hard	11.2	6.4	13
Primary Branches	10.0	0.0	2		Rotten	20.5	14.3	8
Nub	9.0	0.0	1					
Hard	11.6	7.3	10					
Rotten	20.5	14.3	8					

Notes:
a - age of needle and leave decay classes are assumed to be 1 year.
b - twig decay class data was not available for deciduous trees, so conifer data was used as a surrogate.

Table 3. Age statistics for unpooled and pooled decay classes of recruited wood are shown for conifers and deciduous wood in the Klamath, Cascade and Sierra groups (all combined).

Unpooled					**Pooled**			
				Conifers				
Class	**Mean**	**σ**	**n**		**Class**	**Mean**	**σ**	**n**
needle[a]	1.0	0.1	27		needle	1.0	0.1	27
twig	4.3	2.5	51		twig, branch	5.0	3.9	85
branch	6.2	5.3	34		primary, nub	11.8	7.6	65
primary	11.8	7.6	54		hard, rotten	29.8	17.1	48
nub	11.5	7.8	11					
hard	28.0	17.3	41					
rotten	40.3	12.3	7					
				Deciduous				
leave[a]	1.0	0.1	25		leave, twig, branch	2.0	1.7	53
twig	2.9	2.2	18		primary, nub	6.8	4.9	22
branch	2.8	1.8	10		hard, rotten	12.9	11.0	9
primary	7.0	3.6	13					
nub	6.4	6.5	9					
hard	12.8	4.7	6					
rotten	13.2	20.6	3					

Note:
a - age of needle and leave decay classes are assumed to be 1 year.

Table 4. Wood recruitment rates in m^3/ha/yr for region-forest groups with at least 5 study segments are shown in the first five rows of the table. Only forest mortality recruitment is shown for the remaining groups for comparison of mortality recruitment of managed, less managed, and unmanaged forest categories in the Cascades and Sierras.

Geomorphic Province and Forest Management	Conifer Mortality		Deciduous Mortality		Total Mortality		Bank Erosion		Mass Wasting	
	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ
Coast Unmanaged	1.3	1.3	0.5	0.8	1.9	1.6	2.5	1.7	0.7	1.6
Coast Managed	2.9	5.8	1.7	4.0	4.6	8.5	4.4	4.4	2.5	7.9
Klamaths Less Managed	5.5	10.6	0.8	1.2	6.3	10.6	2.3	1.2	1.0	0.9
Cascades Managed	2.6	3.3	0.6	0.8	3.2	3.7	5.4	11.0	--[a]	--
Sierras Managed	1.6	1.4	3.1	11.8	4.7	11.5	4.5	8.0	--	--
Cascades Unmanaged	3.22	1.7	0.4	0.5	3.66	2.1				
Cascades Less Managed	0.42	0.5	3.54	3.4	3.95	3.8				
Sierra Unmanaged	3.03	--	1.21	--	4.23	--				
Sierra Less Managed	0.9	1.0	0.04	0.03	0.94	1.1				

Note:
a – no mass wasting observed.
-- only a single segment surveyed

Table 5. A comparison of wood storage volumes among this study and two others in California shows both similarities and differences.

Location	**This Study**	**Wooster and Hilton 2004**	**Lisle 2002**
Coast Unmanaged	280-1150 m^3/ha (ave. 830, median 1500)	455-723 m^3/ha (ave. 589)	200-4600 m^3/ha (median 1000)
Coast Managed	300-1100 m^3/ha (ave. 1000)	139-758 m^3/ha (ave. 251)	--
Klamaths Less Managed	0-724 m^3/ha (median 255)	--	18-1600 m^3/ha (median 250)
Cascades mature and old forest	1-125 m^3/ha (median 50)	--	36-100 m^3/ha (median 300)
Sierras old forest	0-485 m^3/ha (median 180)		2.2-100 m^3/ha (median 30)

-- no data

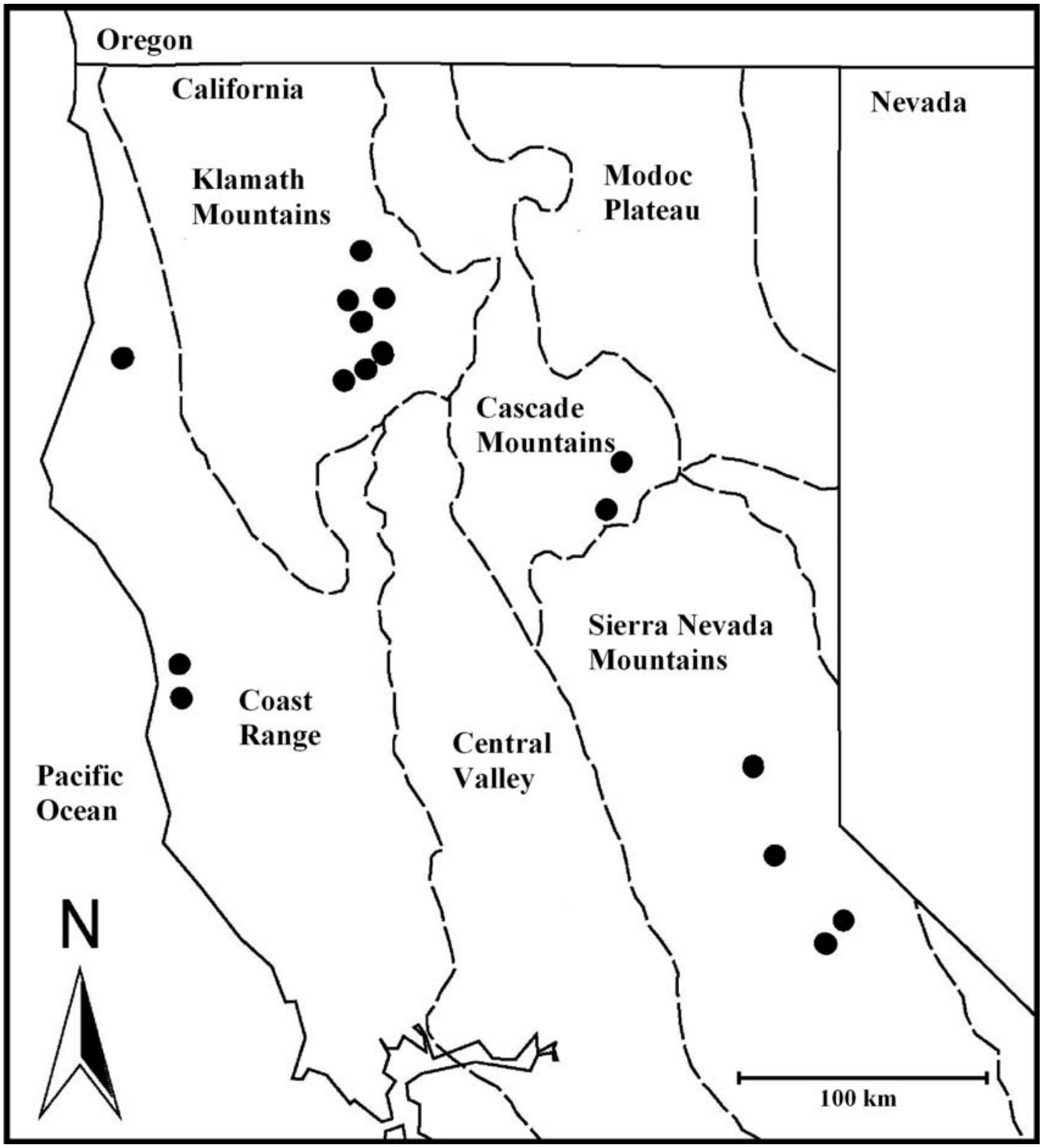


Figure 1. The study sites of wood recruitment, storage and transport are shown within four physiographic regions of northern California. Refer to Table 1 and Figure 2 for information on area characteristics.

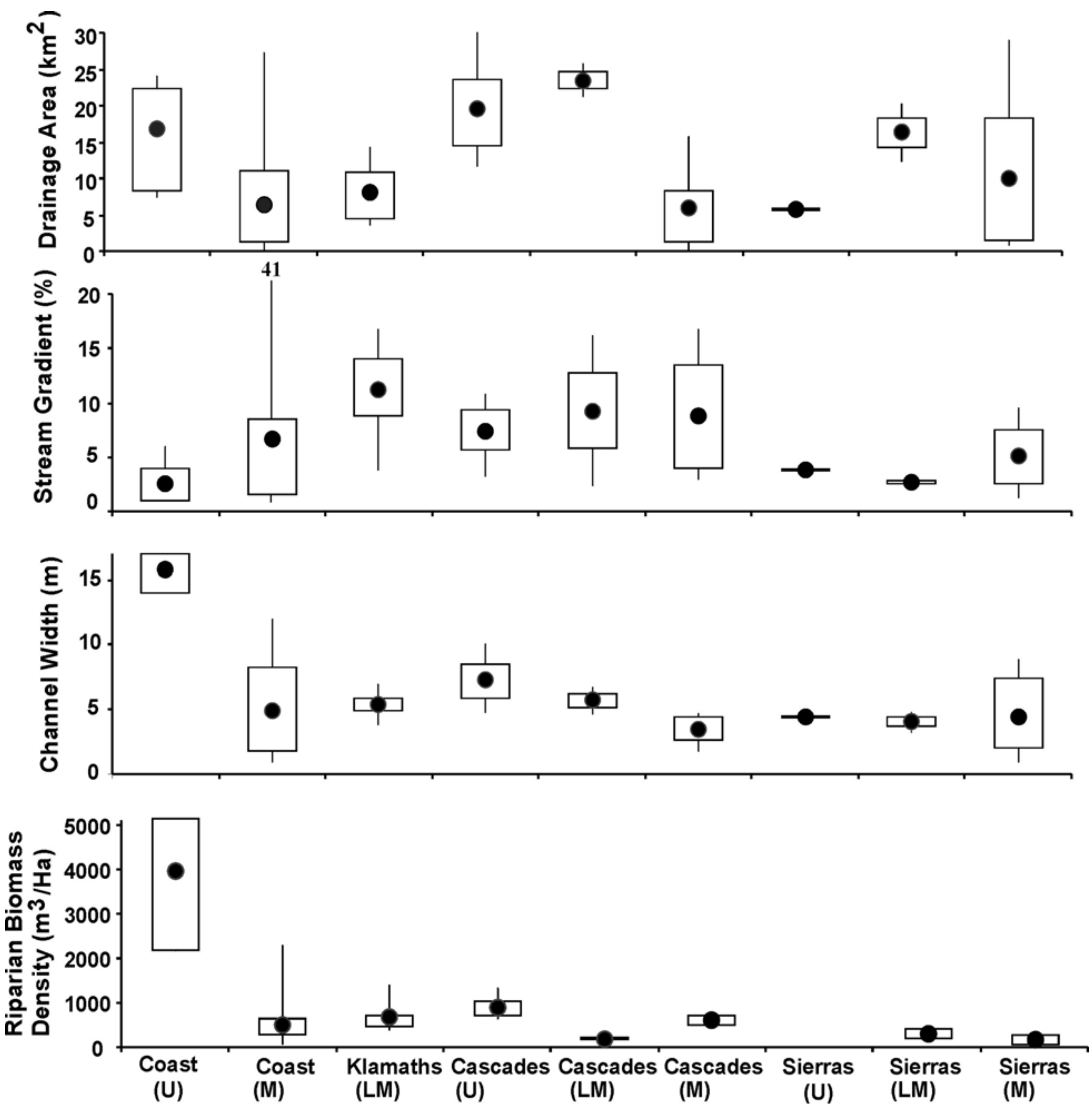


Figure 2. The study sites located across 93 km of streams in northern California are clumped into nine region-forest management groups. Closed circles, box ends, and lines represent averages, quartiles, and ranges respectively. “U”, “M” and “LM” refer to respectively “unmanaged”, “managed” and “less managed”; refer to Appendix for detailed descriptions of the management histories of these categories.

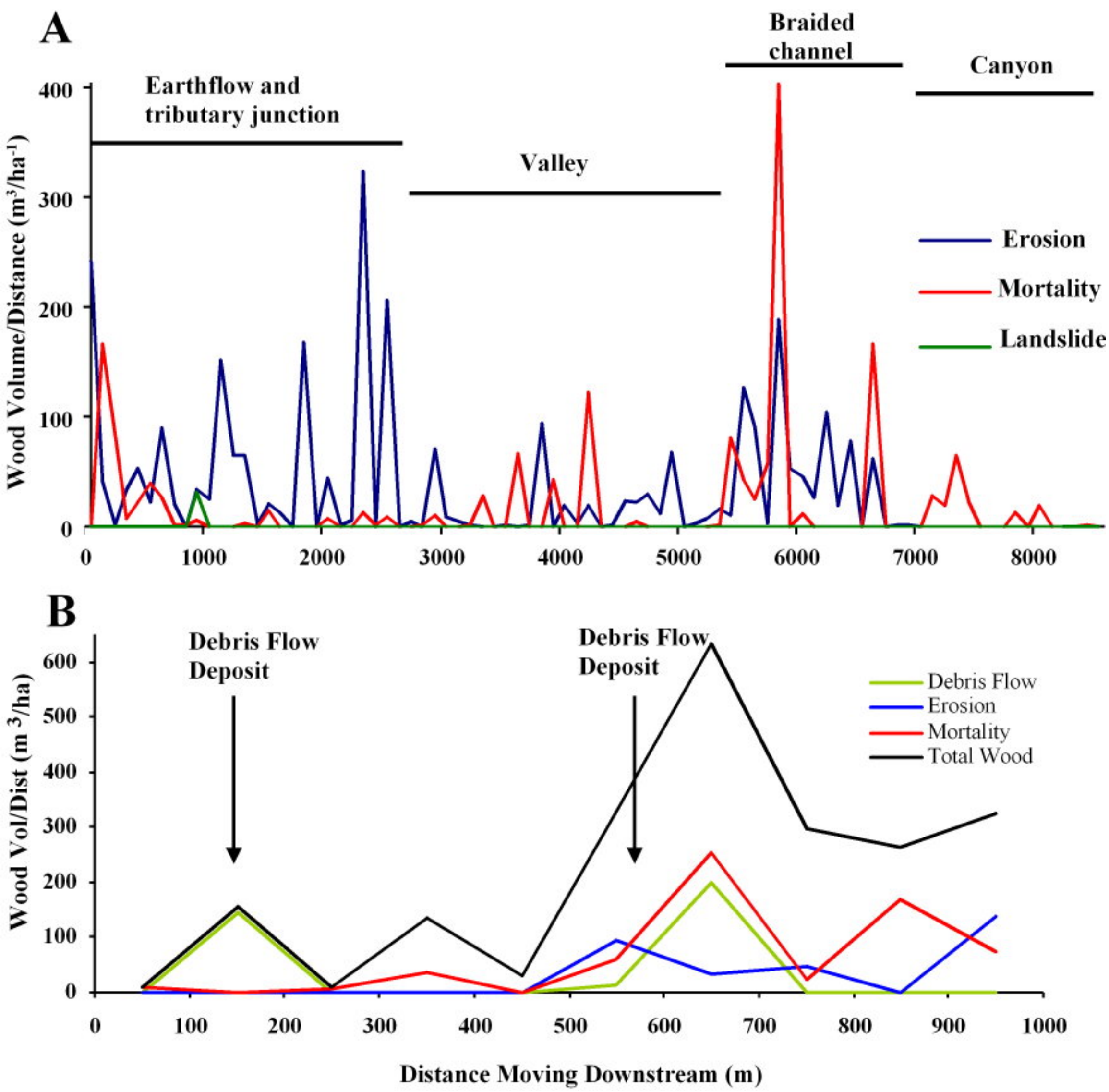


Figure 3. In-stream wood volumes varied due to differences in wood recruitment processes related to earthflows, tributary junctions, stable valley segments, braided channels and debris flows. Two example stream segments from the Sierras (A) and Klamath Mountains (B) are shown. Total wood volume includes in-stream wood that was not linked to a recruitment process.

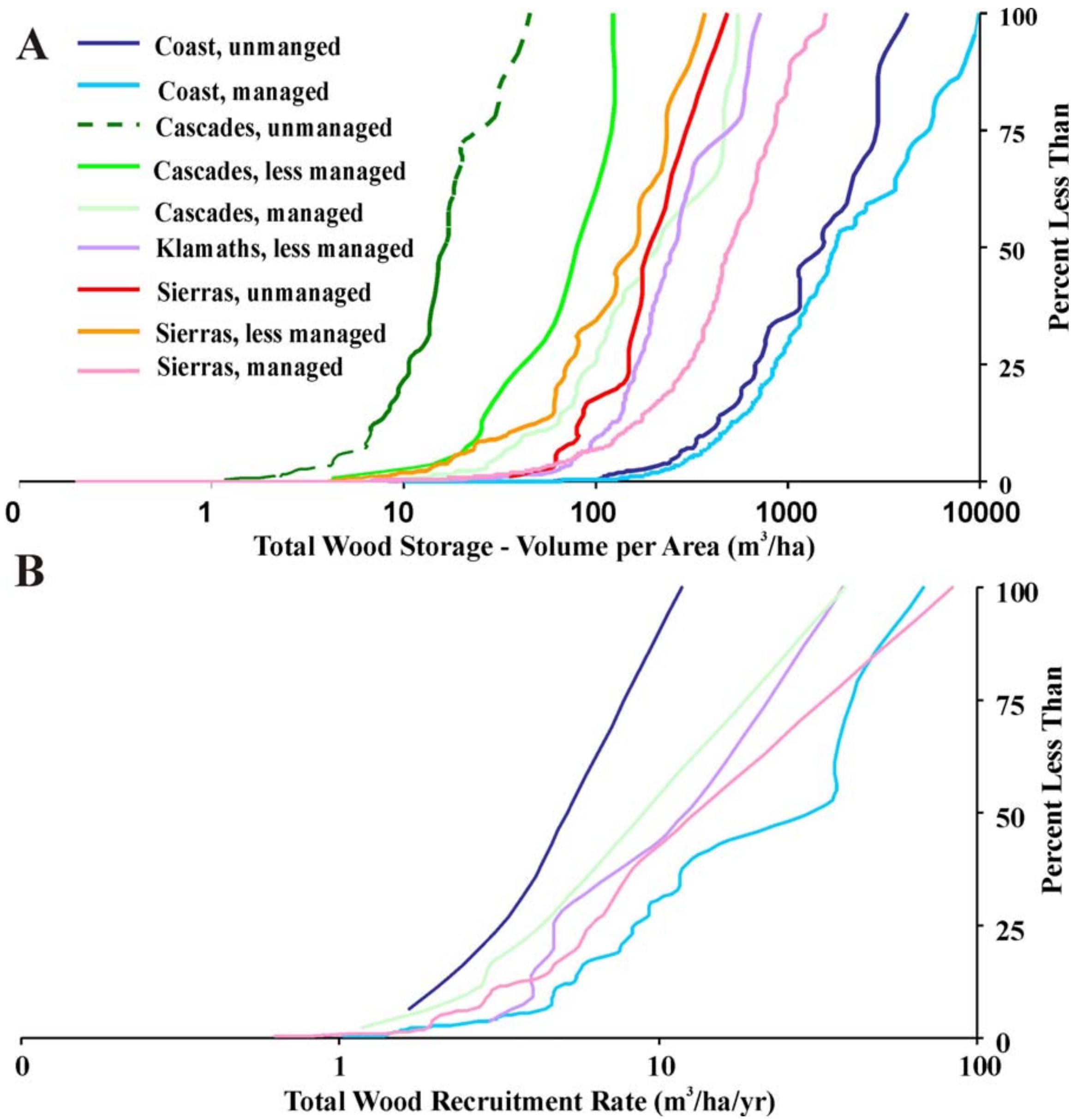


Figure 4. Cumulative distributions of total wood storage (per unit channel area) and total recruitment rate are plotted according to region-forest management groups. Refer to Appendix for detailed descriptions of the management histories of these categories. At least five reaches were required for calculating distributions of recruitment rates (B) a number only available in five region-forest groups.

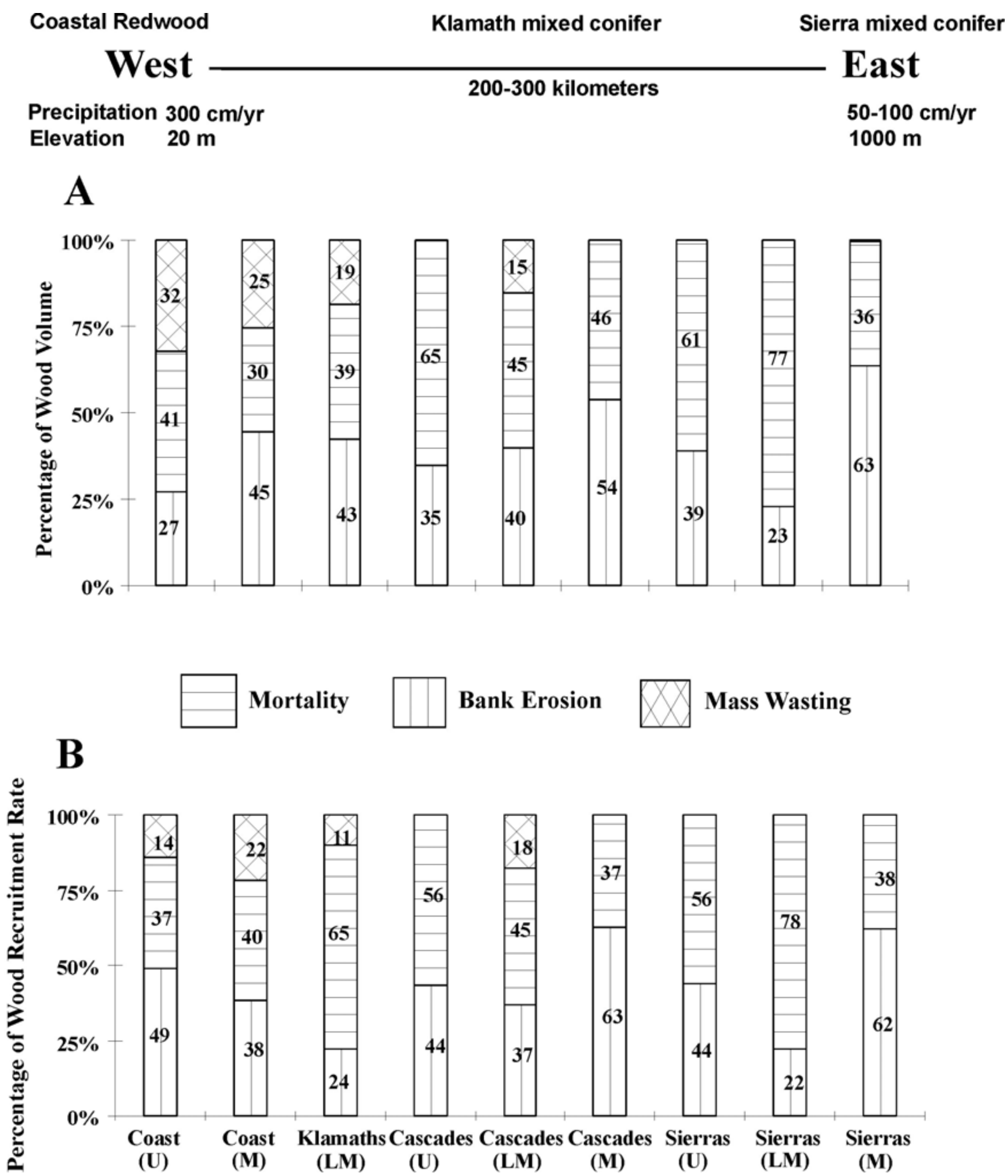


Figure 5. The proportion of wood volume (A) and wood recruitment rates (B) vary by process across the nine region-forest management types in northern California. The precipitation and elevation gradients are also shown. . "U", "M" and "LM" refer to respectively "unmanaged", "managed" and "less managed"; refer to Appendix for detailed descriptions of the management histories of these categories.

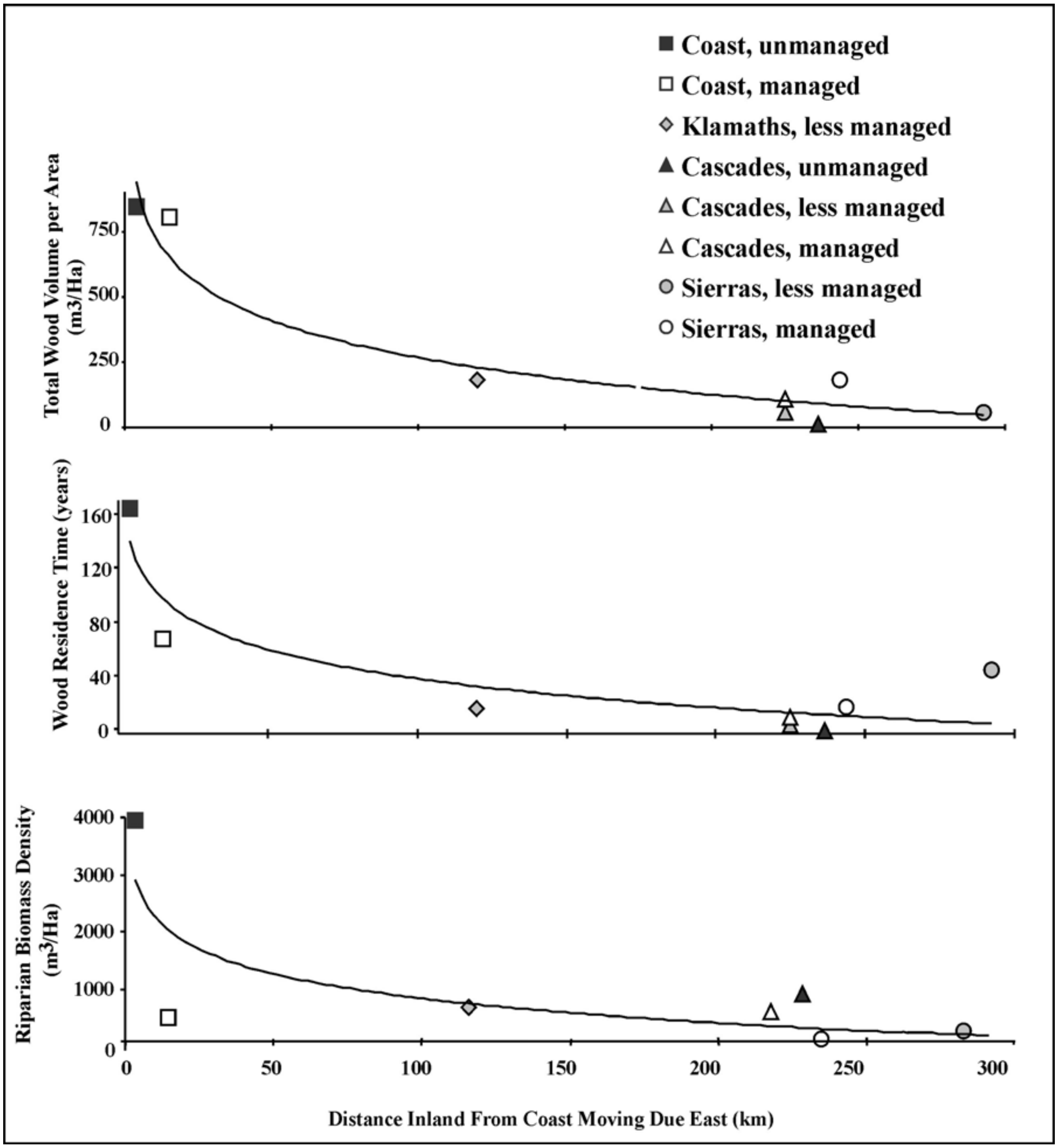


Figure 6. Total wood storage, in-stream wood residence time and riparian forest biomass vary across a 300 km west-east gradient from coast to inland in northern California. The Sierras unmanaged site is omitted because of the absence of forest biomass information**.**

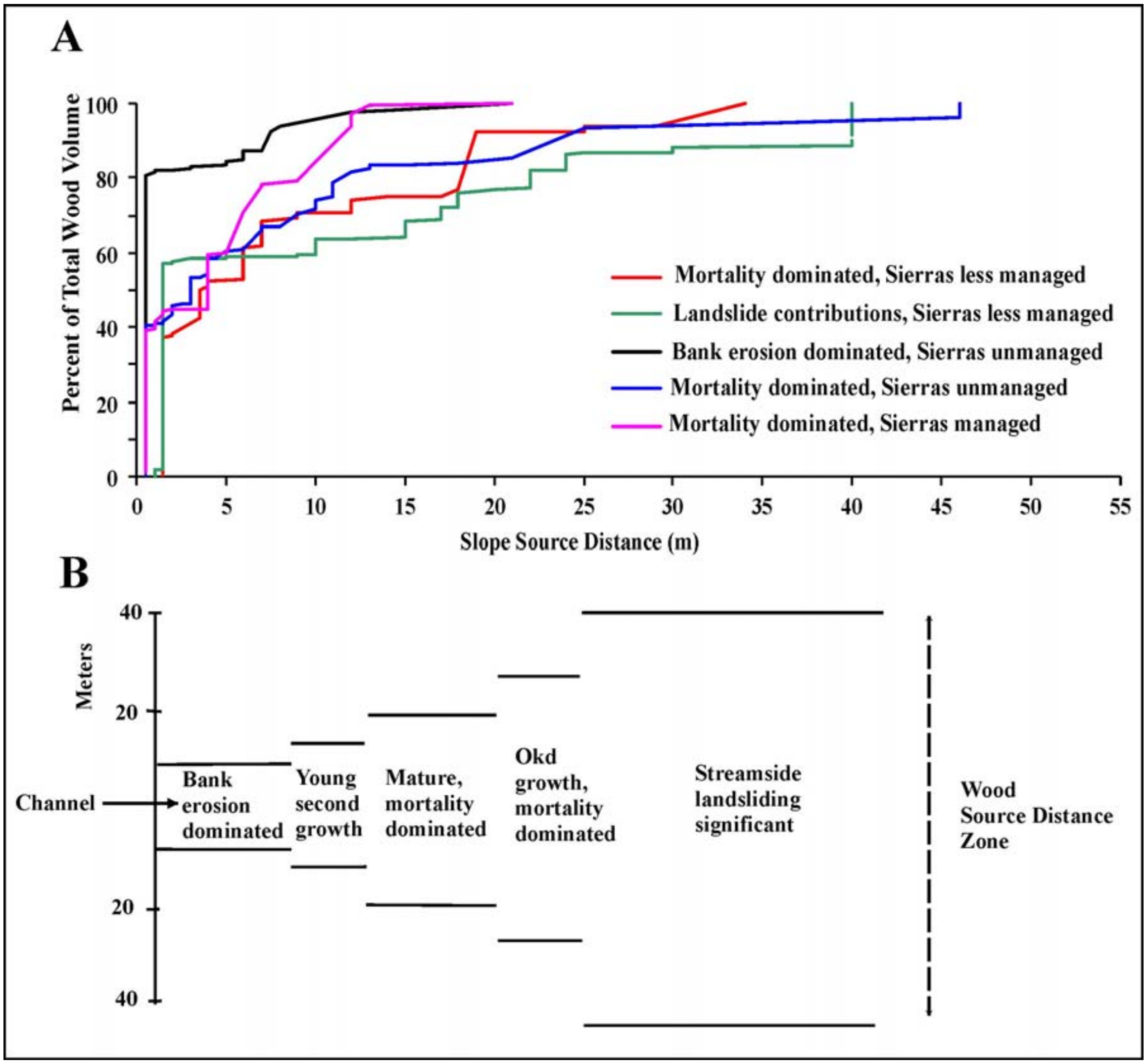
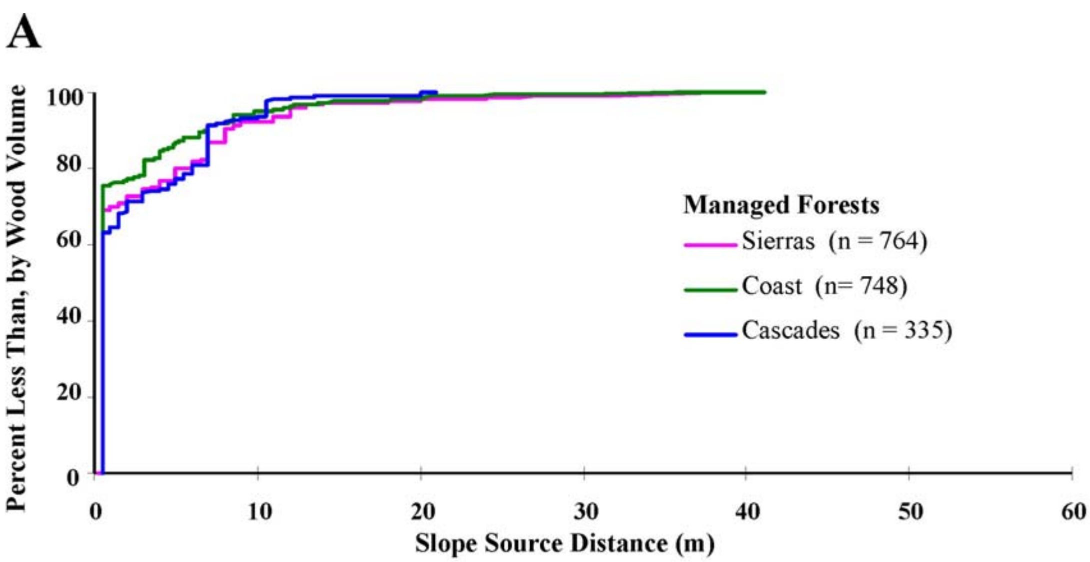


Figure 7. (A) The distance to sources of wood in streams is related to the process of recruitment (bank erosion, mortality, streamside landsliding) and forest management category. Source distances reveal significant variability within one physiographic region. (B) The varying source distances have implications for the design on streamside protection areas.



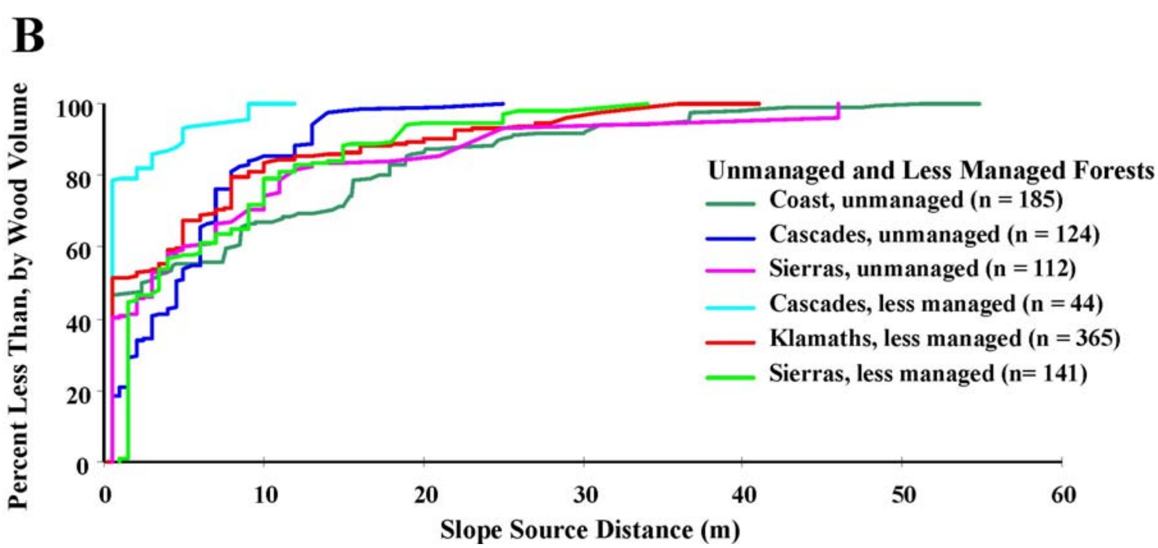
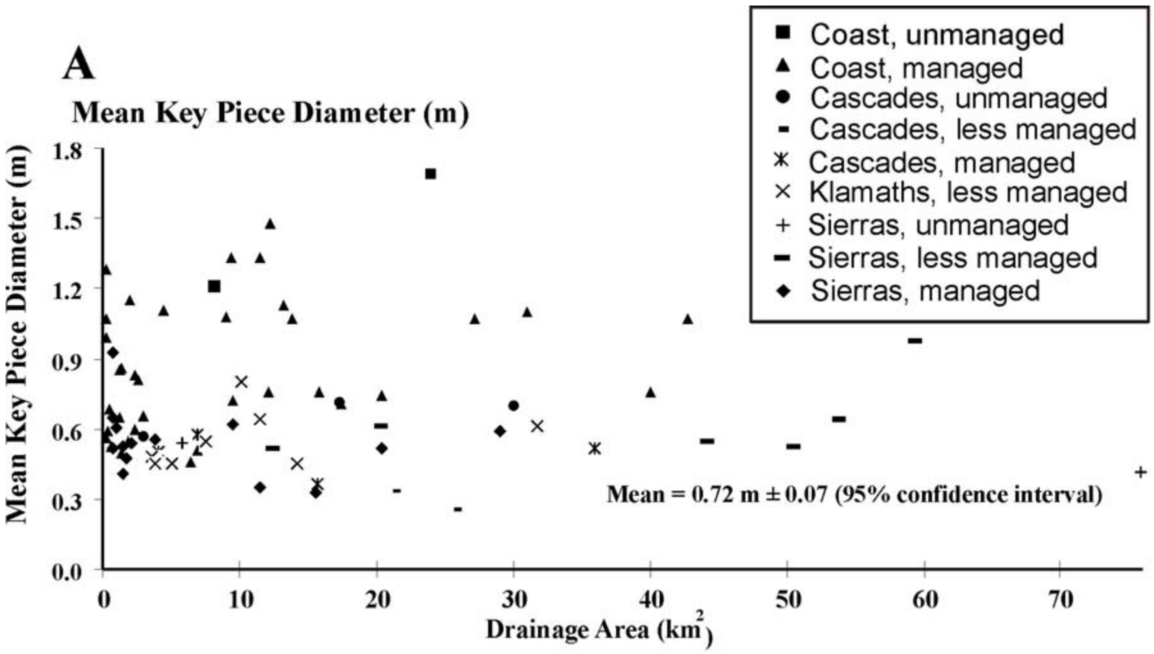


Figure 8. The distance to sources of wood in streams is related to forest management type. (A) In managed forests of the coast, Cascade and Sierra regions, ninety percent of wood recruitment originates from within 10 to 30 m of the channel. (B) In less managed forests, ninety percent of wood originates from within 15 to 35 m. In unmanaged redwood and Sequoia forests, wood recruitment can extend further distances and up to 50 m to attain 90% of wood volume. Data includes all recruitment processes including mortality, bank erosion and streamside landsliding; streamside landsliding occurs in coast unmanaged, coast less managed, Klamath less managed, and Coast and Sierra managed groups.



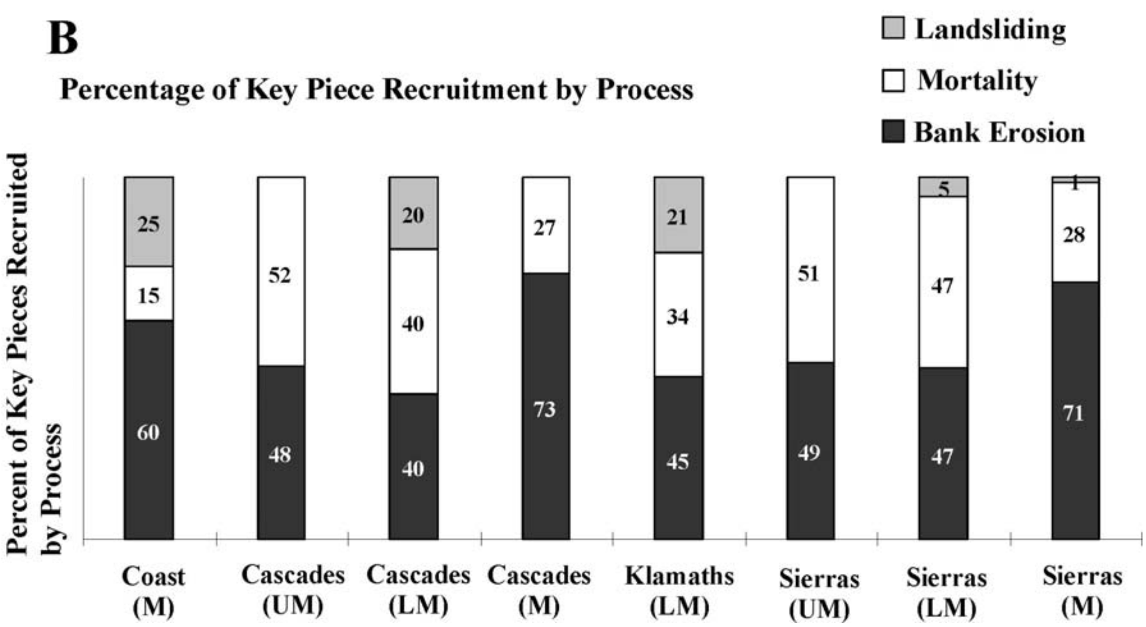


Figure 9. (A) The mean diameter of pieces that create log jams (key pieces) ranged from 0.27 to 1.7 m and averaged 0.72 m. (B) The recruitment of key pieces of wood to stream is dominated by bank erosion in the managed forests (M). In the less managed (LM) and unmanaged forests (UM), just over half of key pieces originate from forest mortality with most of the remainder by bank erosion.

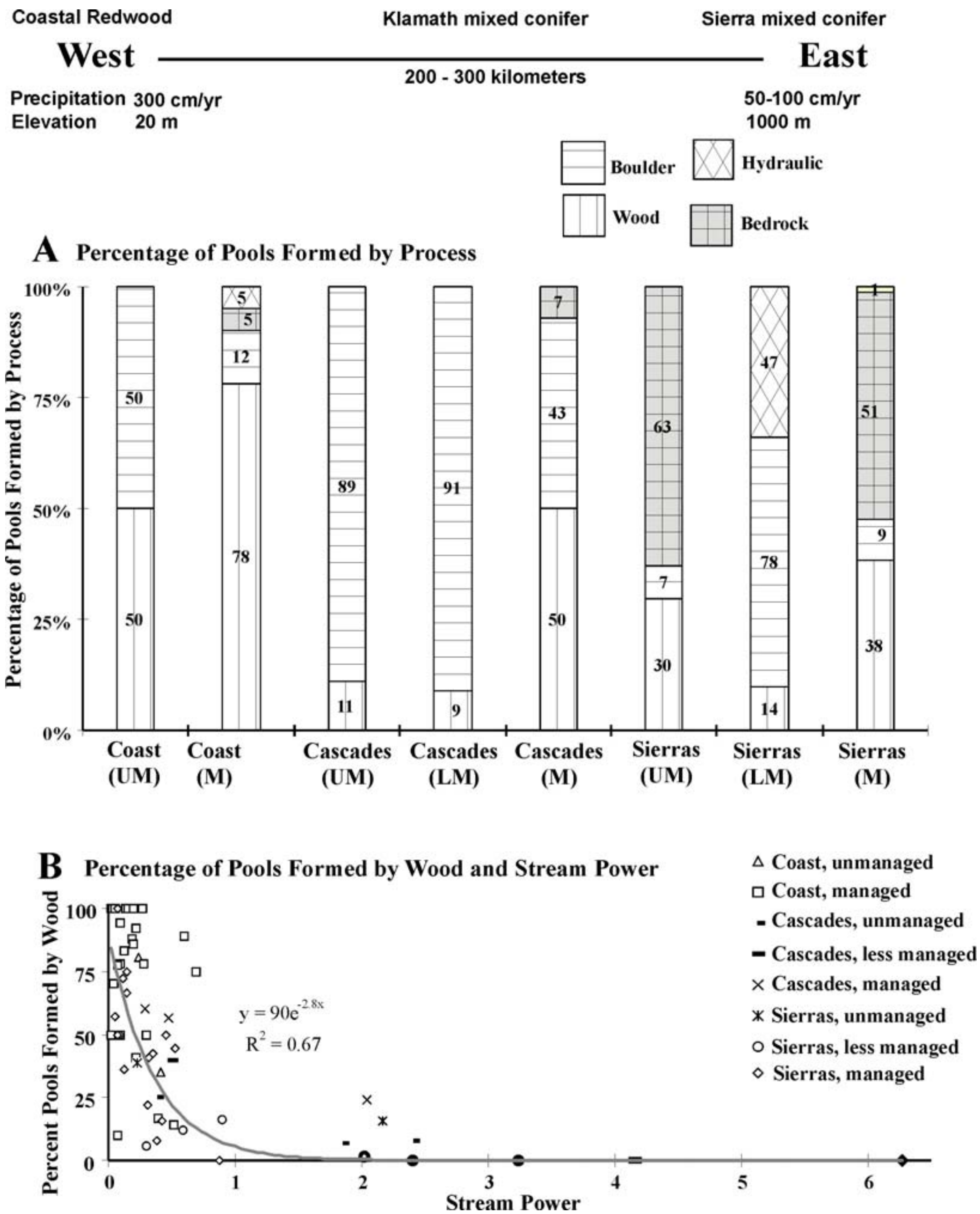


Figure 10. (A) The proportion of pools associated with different processes varied across the nine region-forest management groups. Boulder formed pools dominate in the Cascades and bedrock and boulder pools are important in the Cascades. The largest proportion of wood formed pools occurs in the coastal areas. (B) The proportion of pools formed by wood is highest in channels of lowest stream power. Stream power is the product of slope and drainage area. UM, M and LM refers to unmanaged, managed and less managed forest categories; see Appendix for additional information.

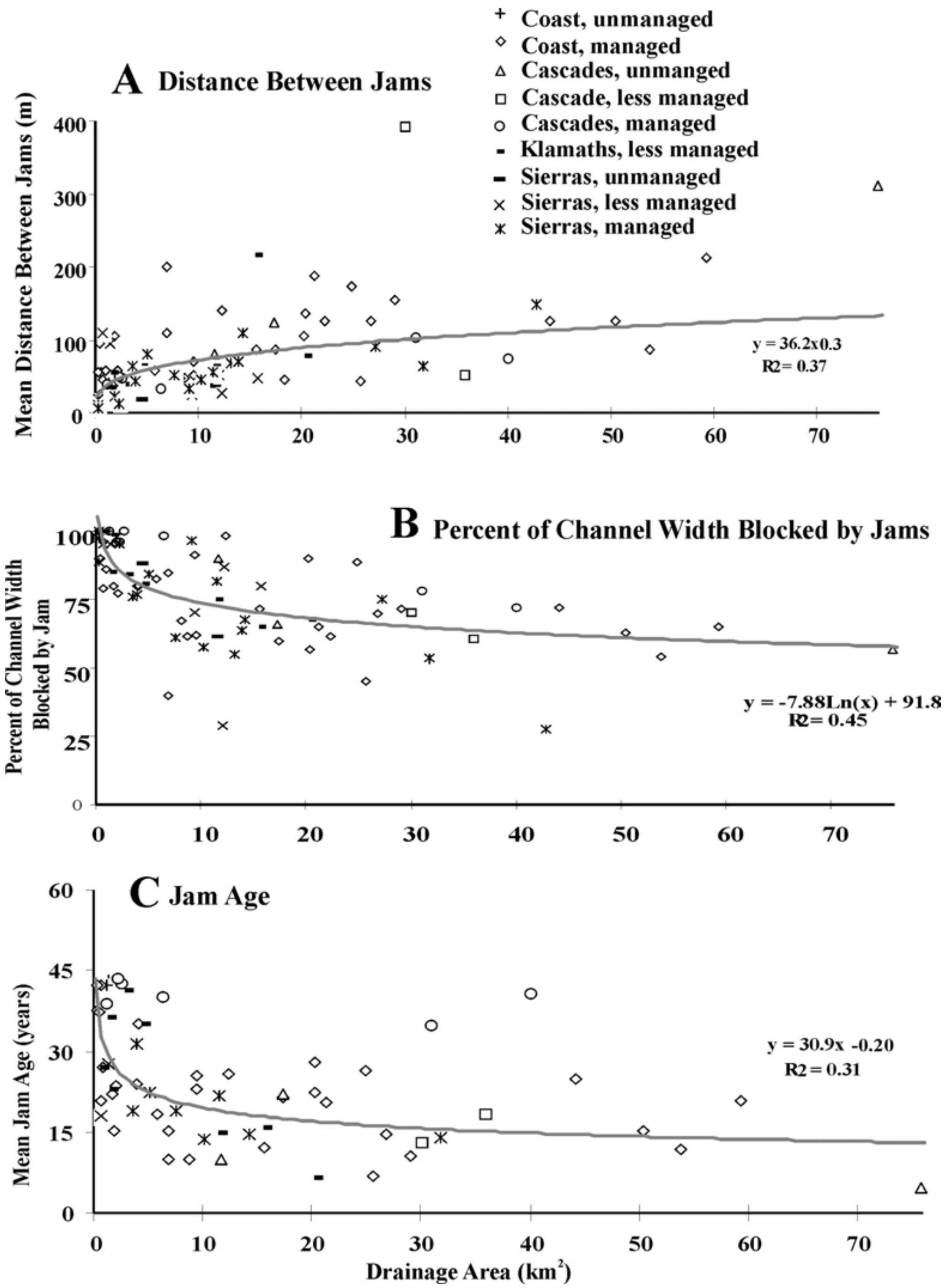


Figure 11. The distance between log jams (A), percent of channel blocked by jams (B) and jam age (C) vary with drainage area. These relationships are used in Equation 4 to predict average transport distances of wood.

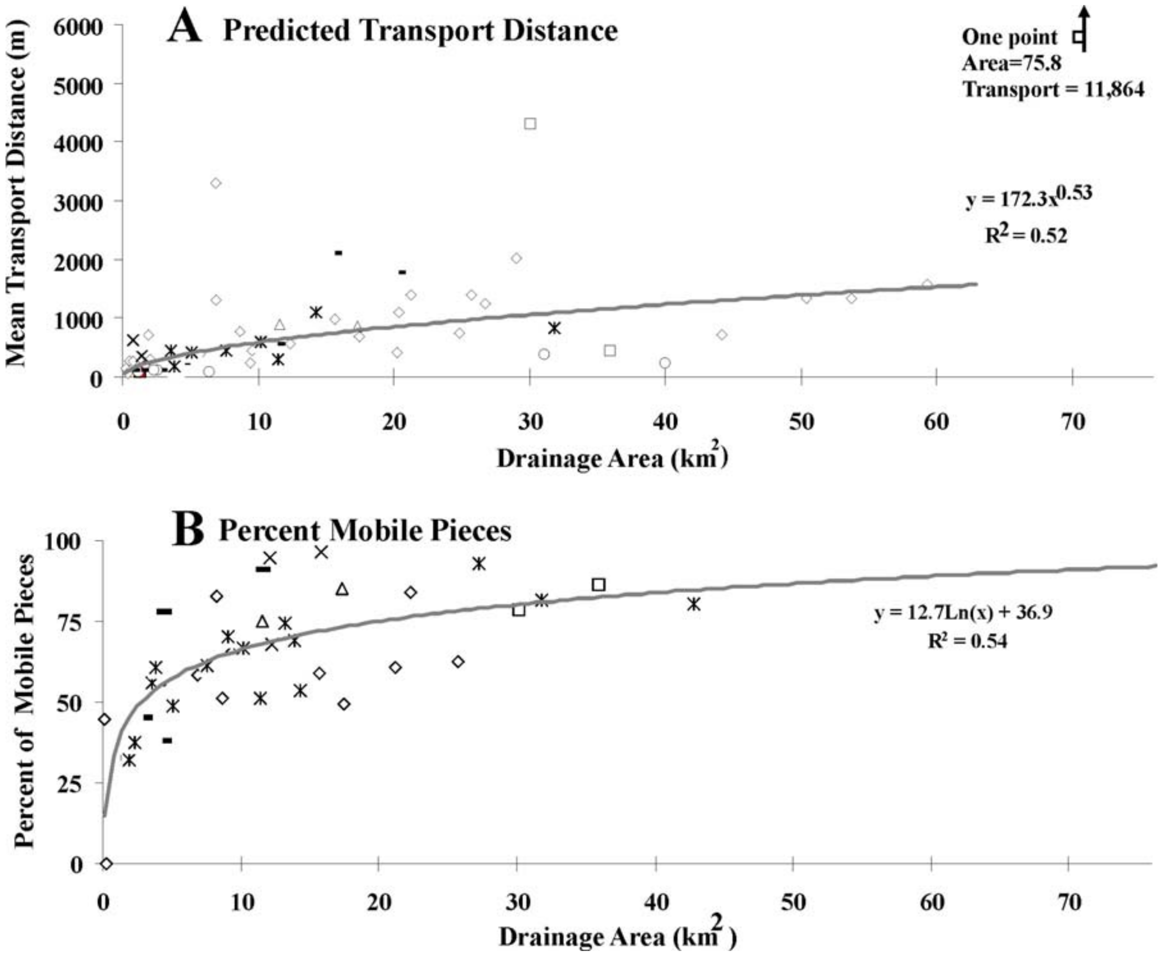


Figure 12. (A) Using Equation 4 and the regressions in Figure 11 (for distances between jams, proportion of channel blocked by jams, and jam age), and assuming a lifetime of wood in streams of 100 years (using a 3%/yr wood decay rate), wood transport is predicted for drainage areas of 1 to 70 km^2. (B) Assuming that fluvially mobile pieces are shorter than the channel width, the percent of mobile pieces increases downstream.